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(54) Rectangular capillaries for capillary electrophoresis.

(57) An elongated or rectangular cross-section capillary 12 is disclosed for use in capillary electrophoresis using optical detection 10, 14. With rectangular capillaries, heat is efficiently dissipated which permits large volume applications in capillary electrophoresis. In addition, the increase in cell pathlength between the source 16 and detector 18 produces significant improvements in absorbance detection sensitivity. This advantage is also important for laser-induced fluorescence, optical rotation, and other pathlength-dependent detection schemes. Because flat walls produce less optical distortion than circular capillary walls, rectangular capillaries are particularly useful when parameters such as refractive index, photodeflection, direct visualization or particle counting are used for detection. Capillary electrophoresis employing rectangular capillaries also allows for two-dimensional separations, the lateral separation being detected with a segmental detector 14.

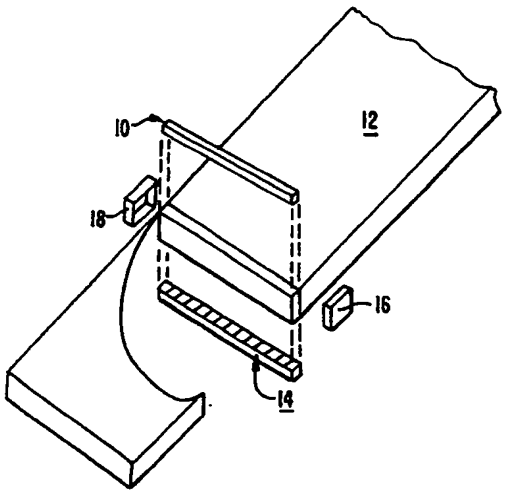

FIG._14.

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RECTANGULAR CAPILLARIES FOR CAPILLARY ELECTROPHORESIS

This invention relates in general to capillary devices and in particular to rectangular capillaries useful in capillary electrophoresis (CE), particularly in capillary zone electrophoresis (CZE).

Capillary electrophoresis is one of the most powerful separation techniques for the analysis of a wide variety of complex mixtures. The technique is capable of orders of magnitude higher resolution than high-performance liquid chromatography; moreover, with CE work it is possible to analyze nanoliter samples. In the past, separation in CE has been exclusively performed in circular capillaries with internal diameters between 5 and 200 microns. The small size of the capillary allows extremely efficient heat dissipation, but as the capillary dimensions are increased beyond 100 microns, a dramatic decrease in separation efficiency is observed. Consequently, CE cannot be scaled to larger diameter capillaries, even with efficient cooling of the outside of the capillary by heat transfer fluids. Furthermore, with circular capillaries, CE cannot be used for ultra-low concentration applications. That is, while the mass sensitivity of CE is outstanding, detection methods still remain the "Achilles heel" of the technique. The ability to detect low concentrations in a 100 micron capillary is difficult, especially when using the very common technique of UV-Vis absorbance.

Another inherent problem associated with conventional circular capillaries is the optical distortion caused by the curvature of the capillary walls. This problem is particularly important when optical detection means are utilized. For example, the curvature at the solute (liquid)-wall interface or at the wall-atmosphere (detector) interface will adversely affect refractive index or photodeflection measurements. In addition, when direct counting methods are employed, the curvature of the capillary walls can cause inaccurate counts.

CZE in small capillaries has proven useful as an efficient method for the separation of solutes. An electric field is applied between the two ends of a capillary tube into which an electrolyte containing the solutes is introduced. The electric field causes the electrolyte to flow through the tube. Some solutes will have higher electrokinetic mobilities than other solutes so that the solutes form zones in the capillary tubes during the flow of the electrolytes through the capillary. However, Joule heating owing to the ionic current carried between the electrodes can result in temperature gradients and subsequent convection and density gradients that increase zone broadening, affect electrophoretic mobilities and even lead to boiling of solvent.

There is a critical need for a capillary device that handles large throughputs and dissipates heat efficiently in CE. Moreover, there is a need for capillary devices with sufficient cell pathlengths so that detection of low concentration samples are facilitated. Furthermore, the capillary device should create minimal optical distortions. Finally, conventional circular capillaries are not suitable for two-dimensional CE separation. A need exists for capillary devices that offer this option.

The device of this invention is for use in capillary electrophoresis. The device comprises a capillary with an elongated cross-section that is transparent at the detection point. In the preferred embodiment, the capillary has rectangular cross-sectional inner dimensions of approximately 50 by 1000 microns. The inventive devices are referred to below as rectangular capillaries. Various configurations of rectangular capillaries may be employed. These include flexible capillaries, ultra-thin channels formed between plates, and corrugated structures. With rectangular capillaries, ineffective heat dissipation no longer presents an obstacle to large volume CE applications. In addition, when optical detection techniques are used, the increase in cell optical pathlength produces significant improvements in detection sensitivity. This advantage is important for laser-induced fluorescence, optical rotation, and also other pathlength-dependent detection schemes. The flat walls produce less optical distortion compared to the walls of circular capillaries. This is particularly important when on column detection is based on parameters such as refractive index measurements, photodeflection, direct visualization or particle counting.

Capillary electrophoresis using rectangular capillaries allows for two-dimensional separations. For instance, creating any gradient across the separation channel of a rectangular capillary while applying an electric field along the length of the capillary provides for a two-dimensional separation. The invention will be further described by way of example, with reference to the accompanying drawings, in which:

Figure 1 shows a rectangular capillary.

Figure 2 shows a rectangular capillary with a flexible configuration;

Figure 3 shows flat, rigid, ultra-thin channels formed between two plates;

Figure 4 shows a corrugated configuration formed by folding a rectangular capillary;

Figure 5 shows a rectangular capillary with a slit situated on the top side of the capillary at which radiation from a detection device is directed;

Figure 6 is an electropherogram obtained with absorbance detection using a rectangular capil-

lary as shown in Figure 5;

Figure 7 shows a rectangular capillary with a slit situated on the side of the capillary at which radiation from a detection device is directed;

Figure 8 is an electropherogram obtained with absorbance detection using a rectangular capillary as shown in Figure 7;

Figure 9 is an electropherogram obtained with absorbance detection using a rectangular capillary as shown in Figure 7; and,

Figure 10 is an electropherogram obtained with absorbance detection using a rectangular capillary as shown in Figure 7.

Figure 11 is a perspective view of a rectangular capillary with magnets positioned to form a magnetic field across the separation channel.

Figure 12 is the separation pattern for three solutes in two-dimensional separation using electric and magnetic field gradients.

Figure 13 is the separation pattern for three solutes in two-dimensional separation using electric and gravitational field gradients.

Figure 14 is a perspective view of a rectangular capillary and a detection device for two-dimensional separations.

An elongated or rectangular cross-sectional capillary is more efficient than a circular capillary at heat dissipation because of greater surface-to-volume ratio; thus, larger (in volume) capillaries can be used while achieving separations with comparable resolution. The rectangular geometry allows the sample size to be increased by at least an order of magnitude – a very important increase when considering CE for preparative applications. The inner dimensions of the inventive rectangular capillaries are about 10 to 200 microns by about 200 to 4,000 microns or more. The inventive capillaries can be manufactured from materials currently used in circular capillaries, including fused silica or borosilicate glass. A rectangular capillary is shown in Figure 1. A high voltage (+-) is applied between the ends of the capillary to move solutes through it.

Besides the use of rectangular capillaries of different dimensions, this invention also encompasses rectangular capillaries of different configurations. For instance, Figure 2 describes a flexible rectangular capillary that, for instance, can be readily inserted into two buffer reservoirs. Figure 3 describes a rectangular capillary that consists of ultra-thin, rigid channels formed between two plates. The plates can be made of fused silica, ceramics, glass or Teflon®. One method for producing ultra-thin channels is fused silica etching; another method is by using thin Teflon® spacers. The distance between the plates are approximately 10 to 200 microns. Finally, Figure 4 describes a corrugated structure formed by folding a rectangular capillary which provides larger cross-sectional areas. As is apparent, this corrugated arrangement does not truly have an elongated cross-section. Although this folded arrangement does not have the same optical pathlength advantage as demonstrated in the flexible rectangular capillary or the flat, rigid, ultra-thin channels, the corrugated arrangement is useful for preparative work.

The degree of detection sensitivity enhancement in CE with rectangular capillaries is ideally proportional to the increase in the pathlength when absorption, fluorescence, or circular dichroism is used. For instance, the use of a 50 x 1000 micron rectangular capillary provides a 1000 micron pathlength and results in a greater than ten-fold increase in sensitivity compared to an 50 micron pathlength capillary. This enhanced sensitivity is demonstrated by the following examples.

EXAMPLE I

A rectangular 50 x 1000 micron (inner dimensions) capillary made of borosilicate glass (Wilmad Glass Co., Buena, New Jersey) was used in a prototype CZE apparatus. See Gordon et al., Science, 244 (1988) for a description of the CZE apparatus and Huang et al. Anal. Chem, 61:7, 766 (1989) for a description of the absorption detector used.

The sample consisted of pyridoxime (1) 2.5 x 10^{-3} M, and (2) dansylated-L-serine 2.9 x 10^{-3} M. The CZE separation was done under the following conditions:

Cell:pathlength 50 μm. Slit 50 x 800 μm.
Split flow 0.5 ml/min. Split ratio 114.
Injector's loop 5 μl.
Recorder 1 cm/min. Full scale 0.02 O.D.
Applied voltage 7.92 kV, current 107 μA.
Column 50 x 1000 μm rectangular.
Column length 50 cm.

Figure 5 shows that for Example I, the radiation from the detection device traverses the height of the rectangular cross-section of the capillary through the transparent slits or sections, thereby providing a 50 μm cell pathlength.

Figure 6 is an electropherogram obtained with the detection geometry described in Example I.

EXAMPLE II

Using the same CZE apparatus and test sample as described in Example I, a CZE separation was performed under the following conditions:

Cell:pathlength 1000 μm. Slit 50 x 100 μm.
Split flow 0.5 ml/min. Split ratio 114.
Injector's loop 5 μl.
Recorder 1 cm/min. Full scale: 0.02 O.D.
Applied voltage: 9.48 kV, current 111 μA.

Column 50 x 1000 μm rectangular.
Column length 64 cm.

Figure 7 shows that for Example II, the radiation from the detection device traverses the width of the rectangular cross-section of the capillary through the transparent slits on the sides of the capillary, thereby providing a 1000 μm cell pathlength.

Figure 8 is an electropherogram obtained with the detection geometry described in Example II.

EXAMPLE III

Using the same CZE apparatus and test sample as described in Example II, a CZE separation was performed under the same conditions as in Example II, except as follows:

Recorder: full scale 0.1 O.D.
Current: 113 μa.

Figure 9 is an electropherogram obtained with the detection geometry described in Example III.

Comparison of the electropherograms for Examples I and II (Figures 6 and 8, respectively) which were obtained at the same detector sensitivity illustrates the significant gain in sensitivity resulting from the greater pathlength in Example II. The increase in sensitivity due to an increase in pathlength is also illustrated in comparing the electropherograms for Example I with that of Example III (Figure 9), the latter was obtained at a lower detector sensitivity. The gain attributed to the increase in cell pathlength can be readily calculated from the electropherograms.

Improvement in detection sensitivity caused by cell pathlength increase is most pronounced when the concentration of the sample is low. For instance, when the concentration of a sample is just sufficient to be detectable in a 50 μm cell pathlength rectangular capillary, by employing a rectangular capillary with a pathlength to 1000 μm, a gain of nearly 20 times is observed.

EXAMPLE IV

Using the same CZE apparatus and 50 x 1000 micron capillary as described in Example II, a CZE separation was performed with the following sample and under the following conditions:

Sample: pyridoxime (1) 1 x 10^{-7} M, and dansylated-L-serine (2) 1 x 10^{-7} M
Buffer: 5 mM phosphate buffer including 5% ethylene glycol

Cell:pathlength 1000 μm. Slit 50 x 100 μm.
Applied voltage 7.68 kV, current 75 μA.
Detection: 310 nm, 0.01 O.D. full scale.

The concentration of this sample is within the ultra-low range where capillary electrophoresis using conventional circular capillaries yields poor results. However, with the larger pathlength of rectanguiar capiiiaries, detection even at these low concentrations is practical. Figure 10 is an electropherogram obtained with the detection geometry described in Example IV.

Besides improving UV-Vis absorbance techniques in CE, the pathlength advantage associated with rectangular capillaries is also important for laser-induced fluorescence, optical rotation, and other pathlength-dependent detection schemes. The rectangular capillary walls being flat instead of curved provide far less optical distortion than circular capillaries. This is important where parameters such as refractive index or photodeflection are used for detection.

Finally, CE using rectangular capillaries allows for two-dimensional separations. For instance, in Figure 11, magnets 2 are positioned to create a magnetic field across the separation channel of a rectangular capillary 4. If an electric field is applied along the length of the capillary, two-dimensional separation occurs.

Figure 12 illustrates a hypothetical two-dimensional separation of a sample containing three solutes A (●), B (O), and C (X) over a period of time. The x-axis designates movement of the solutes due to the electric field along the capillary and the y-axis designates movement of the solutes due to the magnetic field across the capillary. The sample is introduced into the capillary at position 6. As depicted, solute A is strongly affected by the magnetic field, while B is only moderately affected, and C is not affected.

Figure 13 illustrates a hypothetical two-dimensional separation pattern of solutes D (●), E (O), and F (X) in a rectangular capillary where an electric field is applied along the x-axis and gravity acts as the force along the y-axis. The sample is introduced into the capillary at position 8. In this example, solute D, e.g., a large particle with high density, is strongly affected by gravity, E is moderately affected, and F is apparently unaffected by gravity.

Two-dimensional separation can also be accomplished by using pH, temperature and other gradients that will affect the solutes. In two dimensional separation, conventional detection devices such as absorption detectors, fluorescence detectors, Raman spectroscopy detectors, electrochemical detectors, and mass spectrometric detectors can be used. Figure 14 is a perspective view of a detection apparatus for two-dimensional separations. As shown, light source 10 extends the width of one side of the rectanglar analytical capillary column 12. On the opposite side of column 12 is a multichannel detector array 14 to measure the positions and intensities of the solutes which pass by along the width of the capillary. The multichannel detector array thus measures how solutes are influ-

enced by a gradient, e.g., magnetic field, formed across the rectangular capillary. As an option, a second light source 16 can be positioned along the side of the capillary column to focus light across the column. On the opposite side of the column is detector 18. Detector 18 functions to measure the total solute concentration, with the associated pathlength advantages.

It is to be understood that while the invention has been described above in conjunction with preferred specific embodiments, the description and examples are intended to illustrate and not limit the scope of the invention, which is defined by the scope of the appended claims.

Claims

1. A capillary tube for use in capillary electrophoresis using optical detection, characterised in that said tube has an elongated cross-section (Figs. 1 to 5, 7, 11 to 14).

2. A device as claimed in claim 1, characterised in that the capillary tube has transparent sections (Figs. 5 and 7).

3. A device as claimed in claim 1 or 2, characterised in that the cross-section is substantially rectangular in geometry.

4. The device as claimed in claim 1, 2 or 3, characterised in that the inner dimensions of the rectangular cross-section are approximately 10 to 200 microns by at least about 200 microns.

5. A device as claimed in claim 4, characterised in that the dimensions of the rectangular cross-section are approximately 50 microns by 1000 microns.

6. A device as claimed in any one of claims 1 to 5, characterised in that the capillary tube is folded to form a corrugated structure (Fig. 4).

7. A device as claimed in any one of claims 1 to 6, characterised in that the tube encloses a fluid containing a plurality of constituents which move at different speeds in an electric field applied along the length of the capillary, said device further comprising means for applying a gradient across the capillary (Figs. 12, 13).

8. A device as claimed in claim 7, characterised in that said gradient is caused by a temperature differential, a pH differential, an electric field, a magnetic field, or a gravitational field.

9. A device as claimed in claim 7 or 8, characterised by detection apparatus to measure the two-dimensional separation of said constituents.

10. A detector apparatus for use in two-dimensional separation in a rectangular capillary, comprising a multichannel detector array positioned on one side of the capillary channel and a light source on the other side.

11. A device for use in capillary electrophoresis using optical detection, said device comprising a flat, rigid, ultra-thin channel formed between two transparent plates.

12. A device as in claim 11 wherein the distance between the plates is between approximately 10 and 200 microns.

13. A method for two-dimensional separation of mixtures, comprising the steps of:
providing a capillary tube with an elongated or rectangular cross-section;
introducing into the tube a fluid with a plurality of constituents;
applying a first gradient between the ends of the tube;
applying a second gradient across the tube; and,
detecting the constituents separated by the first and the second gradients.

14. Capillary electrophoresis apparatus comprising a capillary tube, and means for applying a potential gradient across at least a portion of the tube in a lengthwise direction, characterised in that the tube cross-section transverse to the direction of the potential gradient has a substantially greater width in a first direction than in a second direction orthogonal to the first direction.

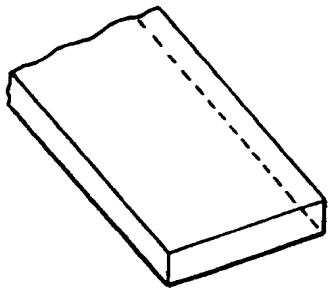

FIG._1.

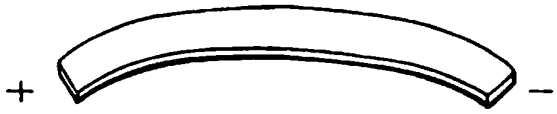

FIG._2.

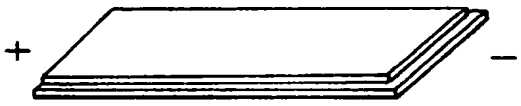

FIG._3.

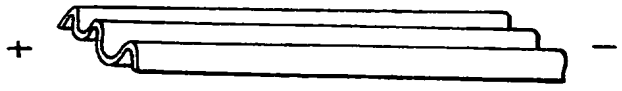

FIG._4.

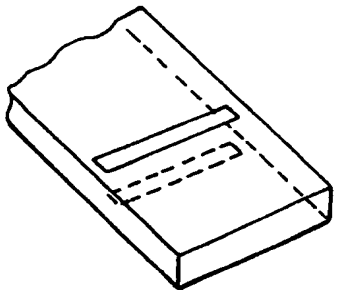

FIG._5.

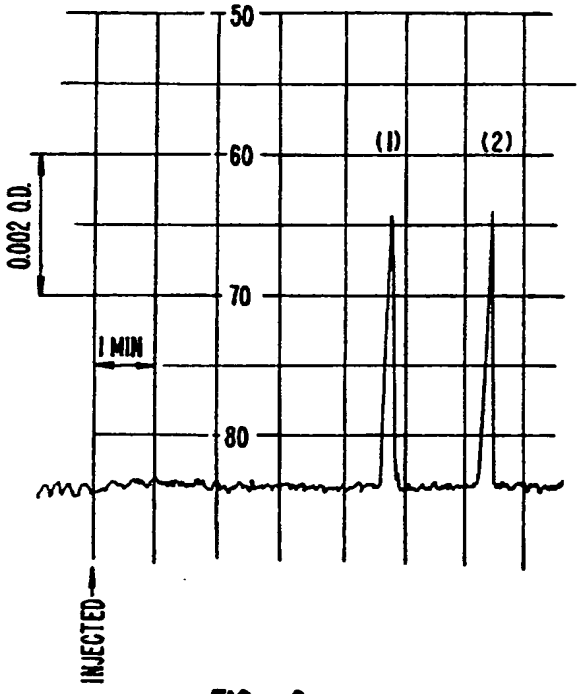

FIG._6.

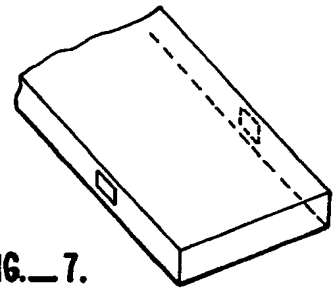

FIG._7.

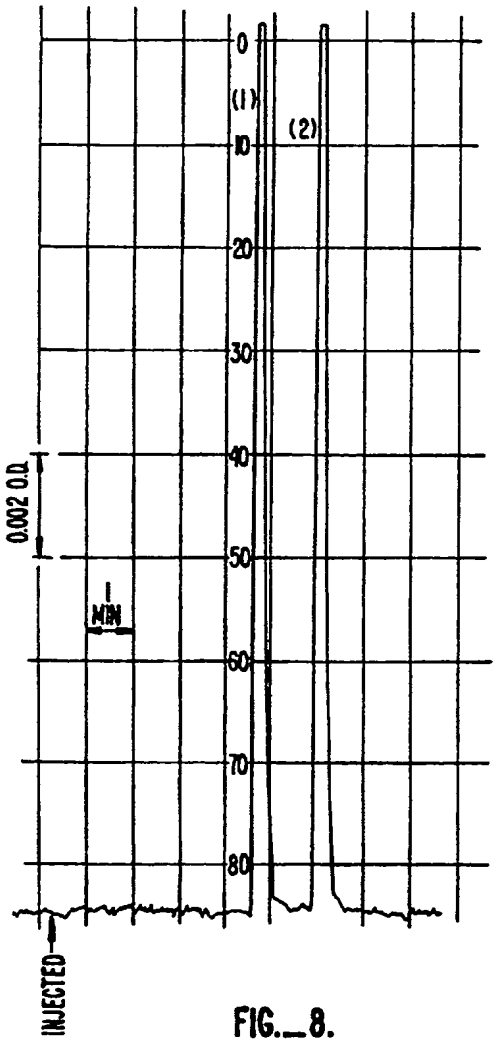

FIG._8.

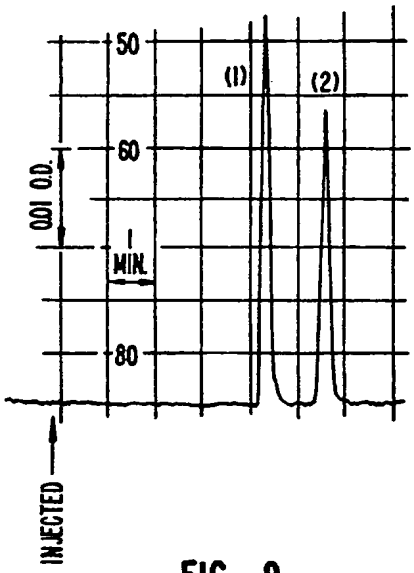

FIG._9.

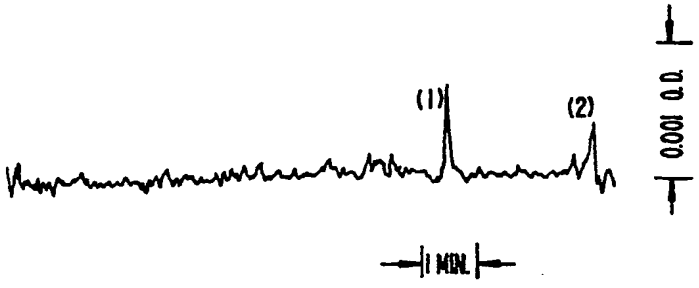

FIG._10.

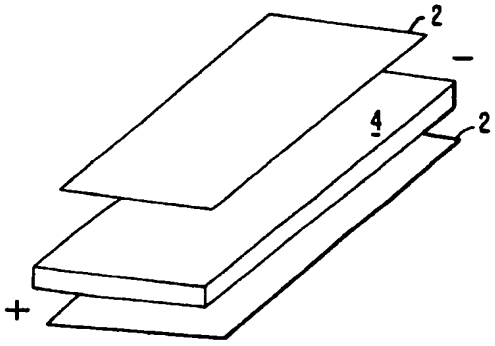

FIG._11.

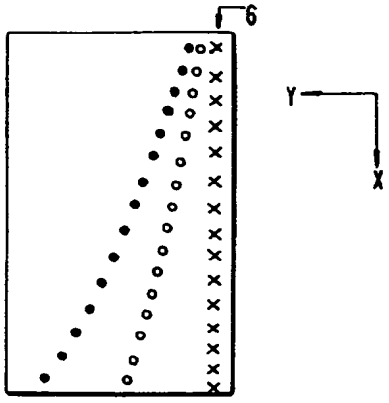

FIG._12.

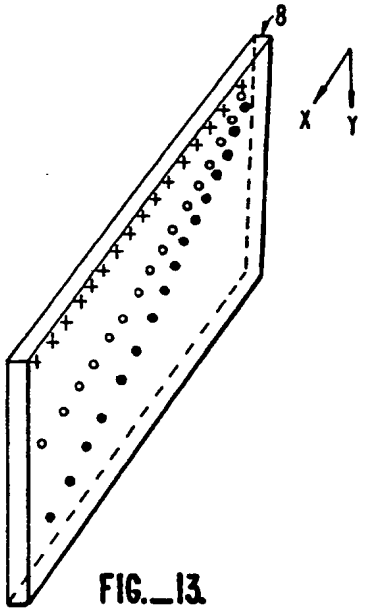

FIG._13.

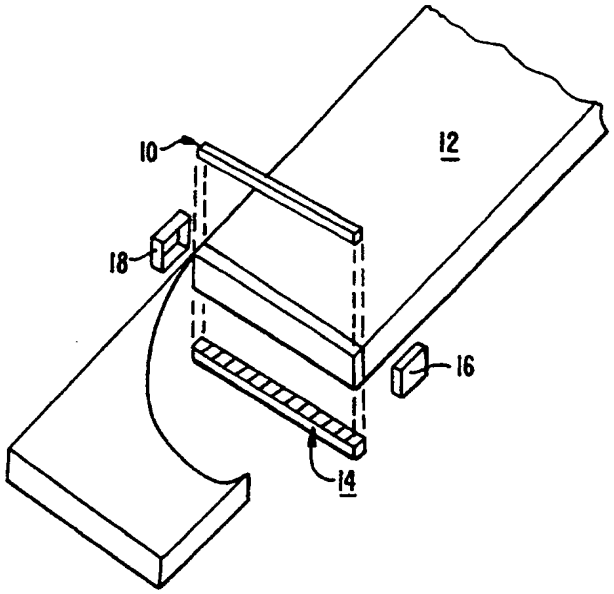

FIG._14.